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DYNAMIC PERFORMANCE OF DIGITAL RECORDERS
USED FOR MONITORING HIGH-VOLTAGE IMPULSE TESTS

ABSTRACT

Recent advances in state-of-the-art high speed digital recorders have made their application possible in the field of high-voltage impulse testing. However, prior to their acceptance for routine testing, the errors introduced in the recording of single-shot impulses must be established. It may be possible to achieve this through a computer simulation which incorporates the dominant sources of error limiting the instrument's dynamic performance. This report describes time- and frequency-domain tests which were performed on the High-Voltage Laboratory's Tektronix 7612D digital recorder. The purpose of these tests was to establish the causes of dynamic error present when recording single-shot impulses typical of those encountered in high-voltage testing. This information will eventually form the basis for a computer model of the digital recorder.

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DYNAMIC PERFORMANCE OF DIGITAL RECORDERS USED FOR MONITORING HIGH-VOLTAGE IMPULSE TESTS

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ABSTRACT

Frequency- and time-domain characteristics of digital transient recorders (in short, digitizers) are discussed in order to establish the requirements on digitizers used for high-voltage testing. Results of an experimental study performed on a 200-MHz, 8-bit digitizer are presented and related to the design features of this instrument. The inherent design characteristics and their influence on the digitizer dynamic performance are analyzed in view of simulation of the digitizer through a computer model.

INTRODUCTION

Digital transient recorders or, in short, digitizers employed for monitoring high-voltage impulse tests have to record non-repetitive (single-shot) impulses with a high degree of accuracy and reproducibility, since even a small deviation between the records of two consecutive impulses may be interpreted as a fault in the insulation of power apparatus under test.

The measuring properties of fast digitizers can be examined in both frequency and time domains [1]. The former method consists of recording a spectrally pure sine signal and subtracting the digitizer output from the "best-fit" sine function. The difference represents the measuring error, and for each signal frequency, the error distribution can be approximated by the Gaussian bell curve in the region between plus- and minus-three standard deviations. Graphs showing the error distribution allow for evaluation of the maximum error as a function of signal frequency, and in fact, indicate the limits of the digitizer's random error. This information proves useful in that it is required to design an appropriate digital (or analog) filter which can be used to reduce this random error. On the other hand, one cannot predict the error limits of an actual record of a high voltage impulse from the digitizer's frequency-domain error characteristics.

The digitizer response to a step function, or to a steep-front impulse of a known form, characterizes the digitizer measuring properties in the time domain [2]. The random digitization error shows up in the form of clusters of points scattered around the rising part of the response, the

form of which depends on the zeros and poles of the digitizer's transfer function. This kind of step response does not allow for correction of recorded impulses by deconvolution, (as can be done with the response of a voltage divider) since the random error implies nonlinear behavior of the digitizer. The degree of nonlinearity is indicated by the random deviation of the recorded digital words from the mean response curve, and in general increases with the steepness of the recorded pulse. An experimental examination of the fastest, commercially-available digitizers was undertaken both in frequency and time domains. The obtained results were analyzed in order to select criteria of acceptance for a digitizer used for monitoring high-voltage impulse tests, and also to develop a computer model simulating the digitizer's dynamic performance. At present, only one model has been thoroughly examined, but characterization of other makes and models is underway.

FREQUENCY-DOMAIN CHARACTERISTICS

An examined digitizer can be first characterized by calculation of the measuring errors of a corresponding ideal digitizer, and as a second step by comparison of those nominal uncertainties with actual measured ones [3]. A sine signal recorded by an ideal digitizer of given resolution (N-bits) and sampling frequency (f_s) is affected by the quantization error (Δ_{quant}) and sampling error (Δ_{sampl}), given by:

$$\Delta_{quant} < |(1/2)*(1/2^n)| \quad \text{and} \quad \Delta_{sampl} < (1-\cos(\pi f/f_s)).$$

A plot of these errors as a function of sine signal frequency is shown in Figure 1 for the examined digitizer. The actual errors measured on this model by two independent laboratories are superimposed on the same graph.

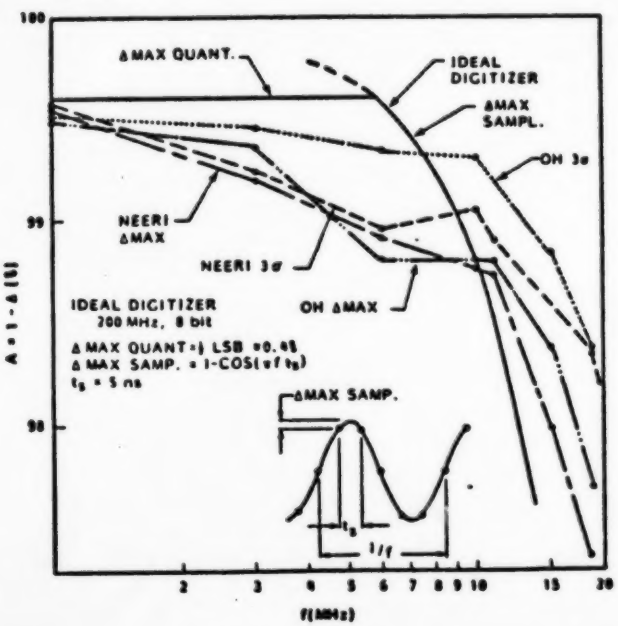

Figure 1
Quantization and sampling error of an ideal 200-MHz, 8-bit digitizer. Maximum and 3σ error characteristics measured by two laboratories (Ontario Hydro and National Electrical Engineering Research Institute of South Africa (NEERI)) on an actual digitizer are superimposed.

The maximum (Δ_{max}) and three-standard-deviation ($\Delta_{3\sigma}$) errors were derived from histograms of the digitization errors and the best-fit Gaussian distributions, respectively. These error histograms are shown with the best-fit Gaussian distributions overlaid in Figure 2.

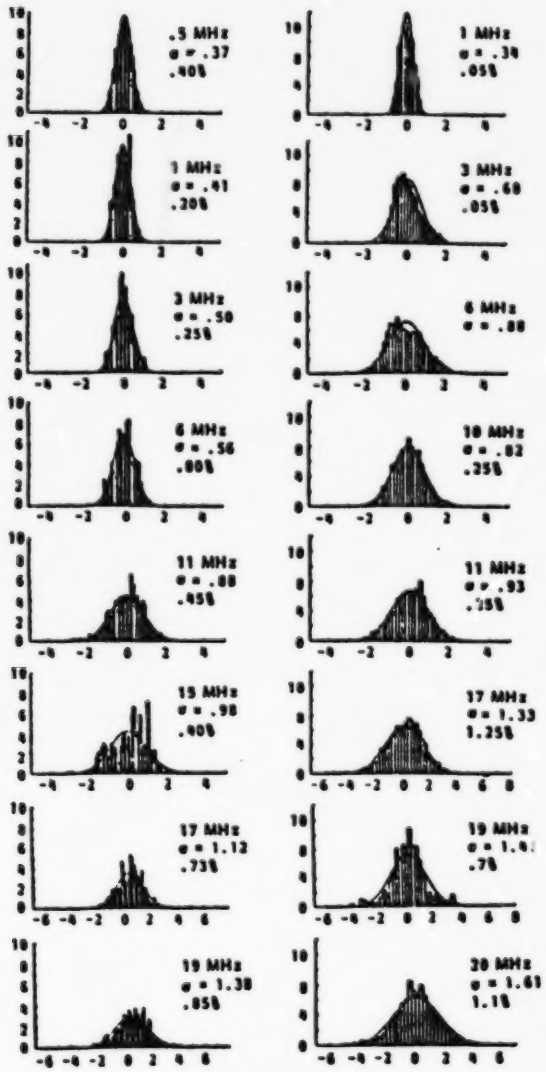

Figure 2

Histograms of the digitization error. The histogram abscissa is graduated in least significant bits (LSB). Signal frequency, standard deviation of the fitted Gaussian distribution, and percentage of errors exceeding $\Delta_{3\sigma}$ are indicated on each histogram.

Formally, the maximum error, Δ_{max}, can only be specified for the number of samples presented in the histogram, and in this study approximately 2000 samples were employed for each histogram. With a sufficiently large number of samples Δ_{max} can be compared to $\Delta_{3\sigma}$ and their ratio may be considered as a criterion of quality of the digitizer.

The presence of large errors, considerably in excess of the 3σ limit of the random error distribution, indicates a malfunctioning of the digitizer circuits. On the other hand, a ratio of Δ_{max} and $\Delta_{3\sigma}$ close to unity does not, by itself qualify the digitizer for use in high-voltage testing. The second, equally important parameter is the value of standard deviation which determines the spread of the random error to be reduced by a filtering algorithm. The larger the standard deviation, the lower the cut-off frequency of the filter required. In consequence, a large part of the digitizer bandwidth has to be sacrificed in order to suppress the random error, and the resulting bandwidth may not be sufficient to cover the frequency spectrum of impulses employed in high-voltage testing.

TIME-DOMAIN CHARACTERISTICS

Response of the digitizer to a step (or a step-like) function contains more complete information on the digitizer measuring properties than the frequency-domain measurements since the spread of digital words around the response reflects the random error component and the response shape characterizes the transfer function of the digitizer input circuits. Unfortunately, there is no direct way to determine the actual measuring error of an arbitrary form impulse recorded by the digitizer with the aid of the step response. However, a family of responses obtained with step-like impulses of increasing transition durations, reveals a gradually decreasing spread of the digital words. For an impulse with a sufficiently slow transition duration, the random error becomes negligible and the digitizer behaves like a linear system. In consequence, the highest steepness of impulses employed for a given high-voltage test should be specified as a criterion of selection of a digitizer which can record these impulses with a negligible random error.

Testing and research on dielectric strength of gas-insulated substations involves generation and measurement of very steep- front high-voltage impulses which may be chopped after a time as short as 0.1 - 0.2 μs. This type of test does not require a very high measuring accuracy, ie, an uncertainty of a few percent on the impulse crest value is acceptable. Impulse tests on internal insulation of power transformers do not involve transients of an extremely high steepness, but on the other hand, the requirements on uncertainty of the digital record are more stringent, ie, the scatter of digital words should be restrained to approximately 0.1 - 0.2% of the crest value.

At present there is no single digitizer which can comply with all these different requirements, but a suitable model can be selected for each type of test. The submicrosecond-duration impulses can be best recorded by 8-bit, 200-MHz (or perhaps 100-MHz) digitizers, whereas 10-bit, 60-MHz models are suitable for monitoring tests on power transformers. At this stage, the study is focused on characteristics of the Tektronix 7612D[1] instrument. Corresponding models from other manufacturers will be examined with the same techniques in the near future.

The experiment consisted of the recording of step-like impulses with controlled transition durations, and a computer-assisted analysis of the digitizer output. The analog input circuitry of the digitizer acted as a low-pass filter, limiting the transition duration of the digitizer impulses to approximately 4 ns, and this imposed a practical limit on the shortest front time. The random digitization error became negligible on impulses with 100-ns transition duration, and these two values delimited the range over which the transition duration was adjusted. A random time lag was introduced between the instant of digitizer triggering and application of the impulse in order to eliminate possible systematic errors in the transfer and storage of the digital output codes. The analysis of the digitizer output comprised detection of the occurrence of all digital codes encountered in the records of the input pulses.

As a result of this processing, the number of occurrences, N_{occ}, of the output digital codes is presented in Figure 3 in the form of histograms plotted for each transition duration (t_d) of the recorded impulse. The number of digital words recorded on the front, N_f, and number of processed records, N_{rec}, are indicated on the histograms. The upper six histograms show data obtained with the digitizer under investigation, while the lowermost gives results found on another digitizer.

The number of samples taken on the impulse front increases with the transition duration, hence, a smaller number of records is sufficient to attain a statistically significant amount of data for the slower pulses.

A particular pattern of digital codes was observed on the first three histograms since only about 20 codes appear out of approximately 150 addressed by the impulse. Moreover, always the same codes appear in the record of the steep-front impulses. The effect of a non-uniform probability of occurrence of digital codes at the high signal steepness has been long known, and is sometimes referred to as the digitizer differential nonlinearity. In general, this term corresponds to the ratio of the actual rate of occurrence of digital codes to the theoretically predicted rate of occurrence which can be derived from the probability density function of the recorded signal. Although a high differential nonlinearity was expected when recording impulses with very short transition durations, the repetitive pattern of occurrence of

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[1] The use of specific trade names in this publication is required to properly understand the results of the experiment and does not imply endorsement or approval in any way of the digitizer in question by any of the participating organizations.

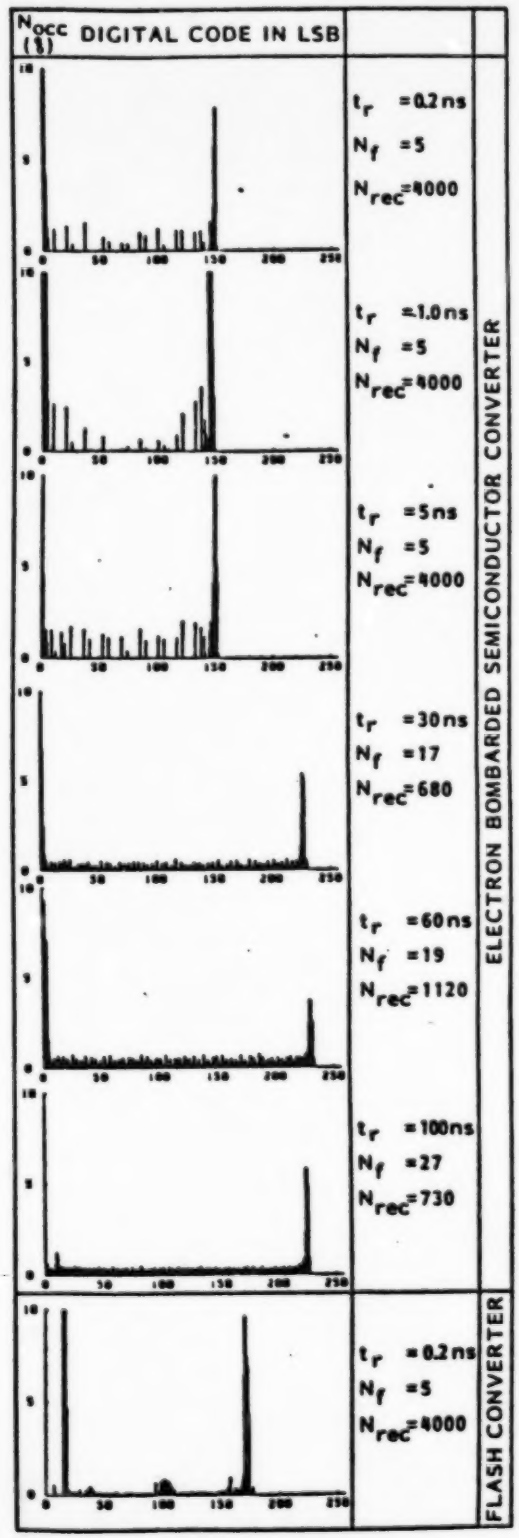

Figure 3

Histograms of occurrence of digital codes construed for impulses with t_d = 0.2, 1, 5, 30, 60 and 100 ns. The first three histograms show a striking similarity. For comparison, a histogram obtained with another digitizer is shown in the bottom line.

several "privileged" codes and persistent absence of any others represented a new feature which had to be explained in order to enable the development of a computer model simulating the digitizer behavior.

The results of a similar test on a different type of digitizer (lowermost histogram of Figure 3) did not indicate the presence of any "privileged" codes. The outstanding difference between the two recorders lies in the analog-to-digital conversion process. This suggested that a close examination of the analog-to-digital conversion technique used in the digitizer under study might reveal the mechanism by which the "privileged" codes are generated.

PARTICULARITIES OF THE ELECTRON-BOMBARDED-SEMICONDUCTOR TARGET

The digitizer in question is built around a device which somewhat resembles an oscilloscope cathode-ray tube, with the phosphorus screen replaced by a target formed of eight adjacent narrow strips made out of semiconducting material used for diodes [5]. Only one set of deflecting plates is installed in the vacuum tube, and the recorded analog signal applied to these plates deflects a ribbon-shaped electron beam which sweeps over the eight-strip target. In front of this target a mask is installed with 256 rows of windows cut out to allow irradiation of the target by the beam. The pattern of these windows corresponds to the Gray code, (ie, each row differs from the adjacent one by only one window) in order to avoid the possibility of major errors in the binary words generated at the diode outputs by the sweeping electron beam. A schematic representation of the electron-bombarded-semiconductor target device developed by the manufacturer is shown in Figure 4.

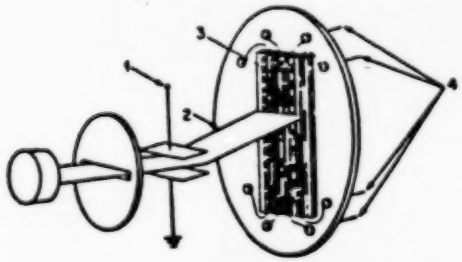

Figure 4

Schematic construction of the EBS fast A/D converter:

1. Input terminal
2. Deflected electron beam
3. Target with mask
4. Gray-code 8-bit output.

It is obvious that the binary signal must be generated on the last bit diode at a fairly high rate when a steep-front impulse sweeps the mask with the electron beam. Effectively, the impulse of 1-ns transition duration generates (at its steepest part) binary "ones" and "zeros" at a rate of nearly 17 GHz on the last bit diode strip, 8 GHz on the first-before-the-last, and 4 GHz on the second-before-the-last. The discharge response time of the sampling diodes prevents the system from accurately tracking such a fast rate of change of input signal, and causes the

overlap of two or more digital codes. This overlapping manifests itself in the occurrence of a random error in the three least significant bits. In order to identify the mechanism of the random digitization error, the Gray-code words generated by the steep portion of impulses with short transition durations were examined. These Gray-code words are shown in Table I.

Gray Code							Decimal	"Privileged" Code
MSB						LSB		
0	0	0	0	1	1	1	5	Yes
0	0	0	1	1	1	1	11	Yes
0	0	1	1	1	1	1	21	Yes
0	0	1	0	1	1	1	26	Yes
0	0	1	1	0	1	1	37	Yes
0	0	1	1	1	1	1	42	No
0	0	1	0	1	1	1	53	Yes
0	0	1	0	0	1	1	58	No
0	1	1	0	0	1	1	69	Yes
0	1	1	0	1	1	1	74	Yes
0	1	1	1	1	1	1	85	Yes
0	1	1	1	0	1	1	90	Yes
0	1	0	1	0	1	1	101	Yes
0	1	0	1	1	1	1	106	Yes
0	1	0	0	1	1	1	117	Yes
0	1	0	0	0	1	1	122	Yes
1	1	0	0	0	1	1	133	Yes

TABLE 1

Distribution of Gray-code numbers with the three last digits equal "one" and indication of "privileged" codes which occur at the steep impulse front

It can be noticed that all the "privileged" codes, which show up during the steep portion of the impulse front have the three last bits locked in the "one" position. Out of all 17 Gray-code numbers which have the three last bits equal to "one" in this range, only two codes (42 and 58) were not recorded.

This observation reveals a mechanism of error generation in the electron-bombarded-semiconductor target digitizer. It will have to be determined how this error changes from one digitizer to another of the same type. If the error pattern is the same, the effect of the last bit locking can be simulated in a computer model. In principle, the random error limits of this type of digitizer can be determined for a given impulse form with the aid of such a model.

FURTHER WORK

The random error occurring at a very high slope of the measured signal will be simulated on a computer model, and the first check of this model will be performed using sine signals. The experimental data have already been collected on the same digitizer, and they can be compared to the results obtained through simulation.

Other digitizers with the same basic parameters, but designed in a different way (eg, dual-rank digitizers composed of two 4-bit monolithic A/D converters and a fast-settling D/A,[4]), will most certainly show another characteristic. An effort will be made to identify their predominant error sources and to develop a representative computer model.

CONCLUSIONS

1. Contrary to frequency-domain analysis, time-domain investigation of the digitizer's dynamic performance has led to identification of the origin of the random error which shows up at the steep part of the records.

2. The effect of locking the last bit diodes at the high signal slope was revealed, and its repetitive character allows for simulation of the instrument performance on a computer model.

3. A different pattern of errors due to limited dynamic performance was observed on digitizers designed with monolithic A/D converters. In consequence, another computer model will have to be worked out to simulate the behavior of differently designed digitizers.

ACKNOWLEDGEMENTS

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